The Validation of Various Technological Factors Impact on the Electron Beam Lithography Process

Agnieszka ZAWADZKA, Kornelia INDYKIEWICZ, Regina PASZKIEWICZ

[1]Department of Microelectronics and Nanotechnology, Faculty of Microsystem Electronics and Photonics, Wroclaw University of Technology, Janiszewskiego 11/17, 50-372 Wroclaw, Poland

agnieszka.zawadzka@pwr.edu.pl, kornelia.indykiewicz@pwr.edu.pl, regina.paszkiewicz@pwr.edu.pl

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Abstract. *One of the most significant processes in micro- and nanoelectronics technology is Electron Beam Lithography (EBL). This technique maintains a leading role in extremely high-resolution structures fabrication process with micro- and nanometer dimensions down to dozens of nanometers. The EBL is a highly complex process and determining fundamental technological factors that affect the final pattern shape is crucial. One of them is the used lithography system, consisting of a substrate and a polymer layer that affects the electron scattering effects. To obtain the required pattern geometry, it is also necessary to properly select the electron beam parameters for given materials. The aim of this work is to discuss the differences in the exposition process for various accelerating voltage (EHT) values. Additionally, the investigation of geometry features and the impact of the exposure dose and the structure dimensions on the final absorbed energy distribution profile in the resist layer is presented and discussed. Numerical studies, using CASINO software and Monte Carlo method, are presented to compare the energy distribution in the polymer that affects the structure formation in the resist layer.*

Keywords

EBL exposition, energy distribution, exposition parameters.

1. Introduction

Recently, the strong development of microelectronics causes that high-resolution techniques for producing microelectronics structures are developing increasingly. It is closely related to the trend of reducing the price of microelectronics devices and increasing their efficiency. One of the high-resolution technologies is Electron Beam Lithography (EBL) that enables pattern fabrication in resist film and then in the utility structures. However, due to its complexity and time consumption, it is applicable only in mask fabrication for optical lithography and for small high-resolution series. The EBL enables submicrometer feature fabrication and, in certain conditions, even smaller structures, down to dozens of nanometers. Obtaining a submicrometer pattern is possible for specific lithography systems with applied resist, precisely calculated electron beam parameters, and development process parameters [1].

In EBL, the final structure shape, dimensions, and profile strongly depend on many technological factors. Therefore, exploiting EBL requires knowledge of the interaction of the electron beam with the lithographic system accompanying phenomena in order to properly select the range of electron beam parameters [2].

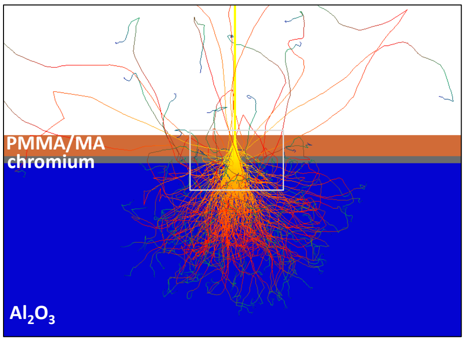
The beam-material interaction leads to the appearance of various signals such as short penetrating secondary electrons and long-range backscattered electrons, which significantly influence electron mean free path and energy distribution [3].

Defining the electron beam accelerating voltage and optimum exposure dose impact on the electron scattering in the material is essential to fabricate desired shapes in the resist layer. Moreover, the lithography system geometry, the type of substrate, and applied resist also affect the scattering effects in the material, spatial deposited energy distribution, and finally, polymer pattern geometry [4].

In the following sections, the technological parameters that impact the resist pattern shape are presented. The influence of accelerating voltage on the final polymer structure shape for different doses and pattern geometries was examined and described.

2. Experimental Details

The analysis of the electron beam interaction with the lithography system (Fig. 1(a)) was executed. The Monte Carlo method was used to predict the penetration of the electrons in the resist and substrate and define its relation to the applied beam parameters. The dependence of energy absorption profile in the material and the e-beam parameters were studied. For this purpose, the Casino software was used [5]. The lithography system consisted of an Al_2O_3 substrate with a 90 nm chromium layer and electron-sensitive Poly(Methyl Methacrylate-co-Methyl Acrylate) (PMMA/MA) ($C_9O_4H_{14}$) resist of thickness 280 nm. The simulations were performed for exposure dose of 25 $\mu C \cdot cm^{-2}$ for 800 nm line exposure. The energy distributions in the material for accelerating voltages of 5, 10, 20, and 30 kV were examined. To define the substrate material impact on the energy distribution in the material, the lithography system based on PMMA/MA on the Si substrate was additionally investigated.



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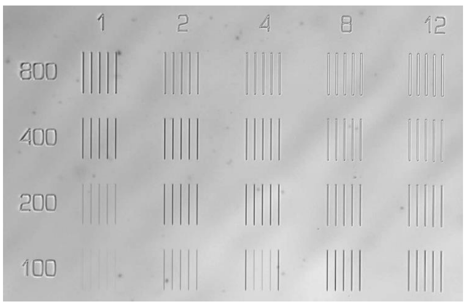

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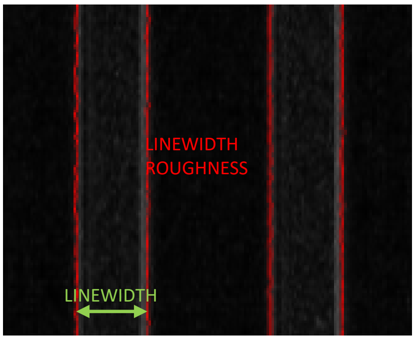
Fig. 1: The lithography system used for EBL simulations with electron beam distribution and trajectory (a) and a fragment of applied test pattern (b).

The impact of the electron beam on the lithography system is schematically presented in Fig. 1(a). The observation area included cross-section rectangle area of 1100 nm by 1100 nm to precisely examine e-beam interaction with electron-sensitive polymer.



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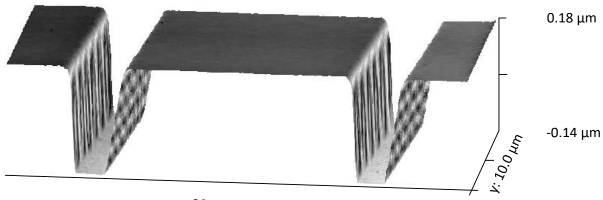

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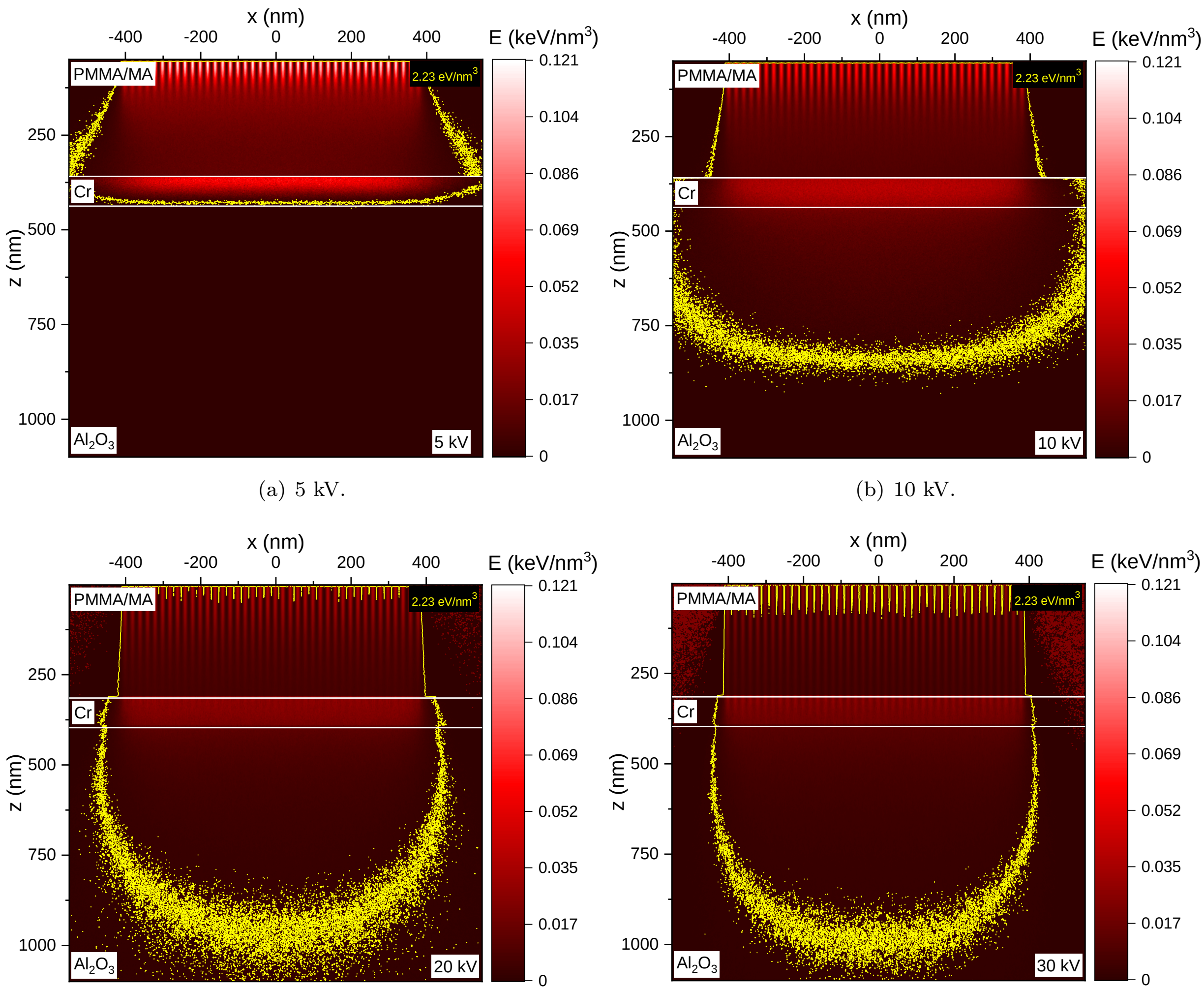
Fig. 2: The horizontal image of resist structures for roughness measurements (a) and the AFM profile of the resist structure for measurements of the pattern width in the cross-sections (b).

The presented lithography system was also used in the experimental part. On the Al_2O_3 substrate, the 90 nm Cr layer was evaporated, and the ARP 617.06 resist layer of thickness of 280 nm was applied by spin coating. The exposition was performed using the Raith Pioneer system in the longitudinal mode. The designed patterned structure, consisting of a series of 100–800 nm wide and 50 µm long lines, are reported in Fig. 1(b). The distances between lines were specified to 10 µm to avoid the proximity effect. Based on numerical analysis, three different EHT values - 5 kV, 20 kV, and 30 kV - were studied. Various exposure dose values of 25, 50, 100, 200, and 300 $\mu C \cdot cm^{-2}$ were applied. To reduce the charging effect, the metal layer was grounded to the sample holder. After the development process, the structures were examined using the optical microscope and Scanning Electron Microscope (SEM). For some 100 nm windows, the used dose and development time were not sufficient to fully expose and properly open resist windows. Therefore, observations were performed for 400 nm and 800 nm windows. The pattern profiles were measured by Veeco Atomic Force Microscope (AFM) and the tapping mode was applied. To evaluate the EHT, exposure dose, and designed width impact on the structure dimensions, the



(a) 5 kV. (b) 10 kV.

(c) 20 kV. (d) 30 kV.

Fig. 3: The simulated absorption profiles in PMMA/MA/Cr/Al_2O_3 for 800 nm line exposition and exposure dose 25 μC·cm^{-2} for EHT of 5 kV, 10 kV, 20 kV and 30 kV.

geometrical parameters of pattern were determined. The average width between two edges and the roughness of edges were described as 3 times the standard deviation of the structure width variation. Measurements of the structure width were made in the middle height of each lithography structure in the cross section, and the roughness was investigated using the horizontal images (Fig. 2).

3. Results

The results of conducted EBL simulations for various EHT values were presented in Fig. 3 Different energy distributions and scattering effects in the materials can be observed for each examined accelerating voltage. The minimum energy level that provokes chemical modification in the internal resist structure was estimated at 2.23 eV·nm^{-3}.

The significant differences in the impact of incident energy on the energy distribution profiles can be observed. The 800 nm line exposure enables the accessible evaluation of the beam parameter impact on the final pattern shape. Although electron beam can be focused to single nanometers, the minimum structure resolution is far away from this regime. The main reasons for this effect are interactions of the energetic electrons with the substrate and the resist layer during the exposure. Electron beam penetrates the lithography system and generates the electron elastic and inelastic collisions with the atoms and molecules of resist and substrate, which remarkably affects the energy distribution. The evident broadening of exposed area to the projected area, as an effect of electrons scattering, can be observed especially for lower EHT values, which results from a larger contribution of short-range secondary electrons, that distinctly limit the resolution. For accelerating voltage of 5 kV, the absorption includes mainly the upper volume of the lithography system. Incoming electron collisions in the upper layer lead to deflecting the paths of the electrons and broadening the beam and the absorption area. Nevertheless, the irradiated area is wider than designed, which can be an obstacle in the fabrication of high-resolution structures when the energy is consumed in the most effective way. For higher EHT value of 10 kV, the electron mean free path increases, but forward scattering still causes that exposed area is also broadened. As EHT rises to 20 kV and 30 kV, the impact of elastic collisions increases, as the mean free path of the electron, which results in lower efficiency of energy absorption in the polymer. The energy penetration area extends deeper into the resist and the substrate that affects the Backscattered Electrons (BSE) interaction shifting and results in uniform energy absorption in the polymer. The generated window dimension matches the projected value. However, the backscattered electrons penetrate deeply into the material, and elastic large-angle collisions may direct electrons back to the polymer layer, affecting exposures even far from the beam input points.

At the same time, it is worth emphasizing that the analysis was obtained for a specific lithography system and each change in the material composition would cause relevant changes in scattering phenomena, subsequent collisions, and electrons' trajectories. Figure 4 presents the simulated absorption profile in the silicon substrate with PMMA/MA for 800 nm line exposure and EHT of 10 kV.

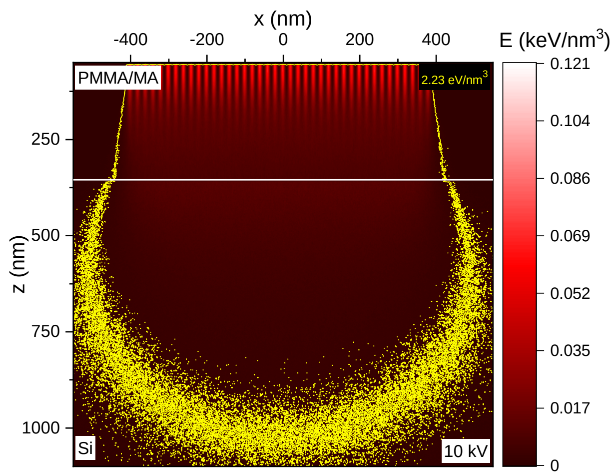


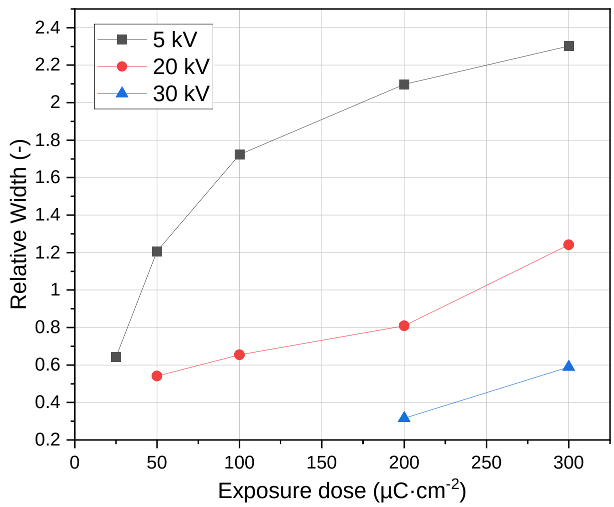
Fig. 4: The simulated absorption profile in PMMA/MA/Si for 800 nm line exposition and exposure dose 25 µC·cm^{-2} for EHT of 10 kV.

Compared to the lithography system based on the Cr/Al_2O_3 substrate (Fig. 3(b)), the energy absorption profile is widened, which is related to the dependence of backscattering also on the substrate nature (atomic number, Z). When modifying the substrate type and increasing its atomic number, the elastic scattering increases and leads to the re-exposures and significant enlargement of the exposure area. In Tab. 1, the atomic numbers for applied materials are presented. This observation indicates the necessity of simulation performing with every change in the lithography system to determine the beam and substrate impact and the beam parameters.

Tab. 1: The atomic Z numbers of applied substrate materials.

Material	Si	Cr	Al	O
Atomic Z number	14	24	13	8

As a result of the experimental part, the windows in resist for various EHT and exposure dose values for different window widths were obtained. For each structure, the middle width of the windows was measured, and for each pattern size, the mean width value was determined. The results are shown in Fig. 5.



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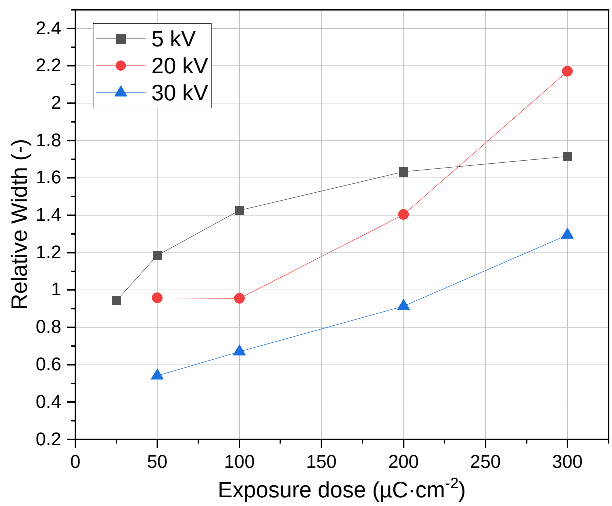

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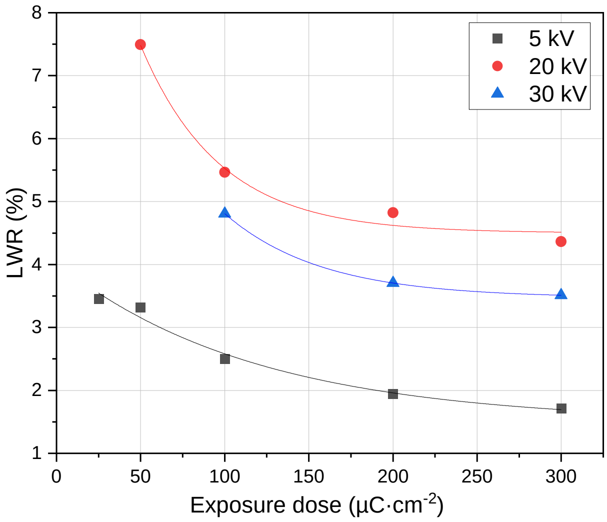
Fig. 5: The relative resist structure width for different EHT values in a function of exposure dose for designed window dimension of 400 nm (a) and 800 nm (b).



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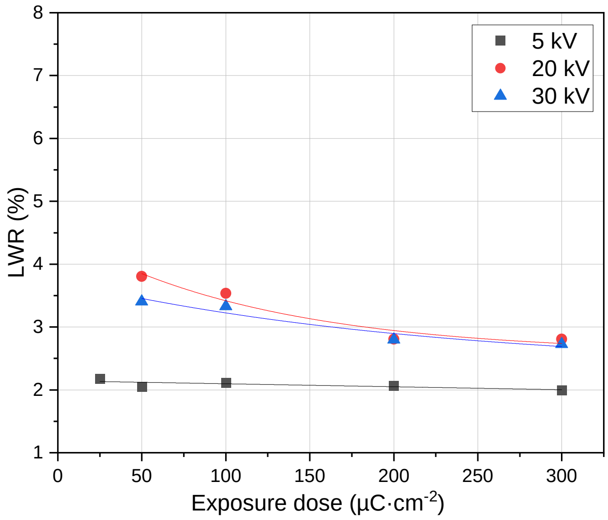

(b)

Fig. 6: The resist structures LWR for different EHT values in a function of exposure dose for designed window dimension of 400 nm (a) and 800 nm (b).

The figures show the essential impact of accelerating voltage on the structure dimensions. At lower applied EHT of 5 kV, the threshold exposure dose value required for PMMA/MA resist was the lowest and the pattern windows were wider. This observation is in agreement with the described numerical qualitative analysis. The reason is the scattered phenomena irradiation area that is located mostly in the resist layer and causes broadening of the exposure area. This dependence is significantly noticed for smaller exposed structures. Increasing the exposure dose causes enlarging the obtained pattern dimensions. It results from increasing the solubility in the developer solution due to decreasing the polymer average fragment after irradiating higher energy. With increasing the EHT values, the lower examined exposure dose was not sufficient for complete exposition and opening the windows in the resist layer for all the linewidths.

The smaller pattern can be fabricated, but the higher dose factor is demanded to obtain desired profiles and due to this, the longer exposure time.

Additionally, the Linewidth Roughness (LWR) was measured based on SEM image processing to compare the resist pattern geometry quality. Figure 6 presents the LWR values of the actual linewidth for different EHT values in a function of exposure dose for linewidths of 400 nm and 800 nm. The percentage values were applied to compare the roughness variations for different nominal linewidths effortlessly.

The crucial impact of EHT on the resist pattern shape and linewidth roughness can be observed. The data points were fitted well with the exponential fit. It indicates that the LWR significantly enhances as the exposure dose value decreases. This is related to the narrower obtained structures and increase of the shot noise impact on fabrication structures. While increasing the accelerating voltage, at the same dose range, the LWR also increases. For both indicated factors, it is related to the relative resist structure width. To obtain minimum LWR value, the dose must be higher, which provokes the decrease in the resolution.

The nonuniformities of the linewidth depend primarily on resist material properties, shot noise, and the statistical fluctuations in the number of electrons in an electron beam and dose fluctuations. The LWR increases rapidly for smaller structures, which entails a substantial problem with fabricating high-resolution structures, where the control of the linewidth is a critical issue.

To improve the structure geometry quality, both the resolution and the pattern roughness, the resists with very high contrast can be applied, and the dose must be precisely defined.

4. Conclusions

In the paper, the significant impact of applied electron beam parameters on the absorption profile in the resist and substrate and the structures geometry was presented and discussed. The different scattering phenomena in the lithography system were shown to be a fundamental restriction in structure fabrication using the EBL process. The material type was shown to be crucial for energy absorption profile and, therefore for electron beam parameters determination. The experimental and numerical results were compared. For low accelerating voltage values, the pattern widening was observed. The application of higher EHT affects minimizing the scattering effects in the polymer layer and improving pattern resolution. The exposure dose was depicted to impact the exposure area distinctly. The LWR was stated to increase as the exposure dose decreases for all the EHT values and structure width. The experimental results were qualitatively consistent with the simulated energy distribution profiles.

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Author Contributions

A.Z. conceived of the presented idea, developed the theoretical formalism, performed the experimental work and numerical simulations. K. I. verified the analytical and numerical methods. Both K.I. and R.P. authors contributed to the final version of the manuscript. R.P. supervised the project.

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About Authors

Agnieszka ZAWADZKA received her M.Sc. degree (2018) in Mechatronics in Faculty of Mechanical Engineering from Wroclaw University of Science and Technology. She is a Ph.D. student at Faculty of Microsystem Electronics, Wroclaw University of Science and Technology. Her current research is focused on technology of semiconductor devices e.g. development of lithography processes.

Kornelia INDYKIEWICZ received Ph.D. degree (2018) from Wroclaw University of Science and Technology, Department of Microelectronics and Nanotechnology. She works in a multidisciplinary team doing research concerning AlGaN/GaN based transistors.

Regina PASZKIEWICZ received her M.Sc. degree (1982) in Electrical Engineering from St. Petersburg Electrotechnical University, Russia and Ph.D. degree (1997) from the Wroclaw University of Technology, Poland. Now she is full professor at Wroclaw University of Science and Technology. Her research is focused on the technology of (Ga, Al, In)N semiconductors, microwave and the development of optoelectronic devices technological processes.